

PLASMON DECAY TO A NEUTRINO PAIR VIA NEUTRINO ELECTROMAGNETIC MOMENTS IN A STRONGLY MAGNETIZED MEDIUM

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Abstract. We calculate the neutrino luminosity of a degenerate electron gas in a strong magnetic field via plasmon decay to a neutrino pair due to neutrino electromagnetic moments and obtain the relative upper bounds on the effective neutrino magnetic moment.

1. Neutrino emission is the main mechanism of the energy losses of stars in the late stages of their evolution [1]. We will consider cooling of the outer regions of neutron stars that are rarefied enough to be transparent to originating neutrinos. Strong magnetic fields ($H \gtrsim 10^{12}$ G) can exist in these regions; moreover, the fields for the class of the neutron stars that are called magnetars can reach $10^{14} - 10^{16}$ G [2] (see also [3]).

Under these conditions, the main processes of neutrino production are annihilation of an electron-positron pair ($e^-e^+ \rightarrow \nu\bar{\nu}$), photoproduction of a neutrino pair on the electron ($\gamma e^\pm \rightarrow e^\pm \nu\bar{\nu}$), photon decay ($\gamma \rightarrow \nu\bar{\nu}$), and two-photon annihilation ($\gamma\gamma \rightarrow \nu\bar{\nu}$). The results of the study of these processes (without a magnetic field) were given in the review [4]. The luminosity of a degenerate nonrelativistic gas via photoproduction of neutrino pairs for the case of a superstrong magnetic field was calculated in [5]. The authors of [6] estimated the luminosity of the degenerate electron gas due to these processes in a superstrong field. The results for photoproduction of neutrino pairs were corrected in [7].

Simple extension of the standard model of the electroweak interactions generates electromagnetic dipole moments of a massive Dirac neutrino (see [1] and a recent review [8]).

2. In this report, we address one of the processes of neutrino emission that is plasmon decay to a neutrino pair mediated by the neutrino electromagnetic moments. As is well known, the plasmon is the photon with a nonzero mass generated by interaction with a medium. A relevant medium model for the outer region of the neutron star is a degenerate electron gas in a strong magnetic field H :

$$T \ll \mu - m, H > ((\mu/m)^2 - 1)H_0/2, \quad (1)$$

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where T and $\mu \simeq \mu(T=0) \equiv \varepsilon_F = (m^2 + p_F^2)^{1/2}$ are the temperature and chemical potential of the gas, ε_F and p_F are the Fermi energy and momentum, $H_0 = m^2/e \simeq 4.41 \times 10^{13}$ G, m and $-e$ are the electron mass and charge (we use the units with $\hbar = c = k_B = 1$). Under the conditions (1), electrons occupy only the lowest Landau level in the magnetic field with $p_F = 2\pi^2 n_e/(eH)$, where n_e is the electron concentration, and the effective photon mass is generated which is equal to the plasmon frequency [9]

$$\omega_p = ((2\alpha/\pi)(p_F/\varepsilon_F)H/H_0)^{1/2}m, \quad (2)$$

α is the fine-structure constant.

Taking into account that for the relatively small momentum of the photon k in the analyzed process the vertex operator of the photon-neutrino coupling (for the Dirac neutrino) is as follows [1, 8] $\Gamma^\alpha = \sigma^{\alpha\beta}k_\beta(\mu_\nu + i\gamma^5 d_\nu)$, we have calculated the luminosity (the rate of energy losses by a unit volume of a medium) due to the process $\gamma \rightarrow \nu\bar{\nu}$ through the electromagnetic channel

$$Q_{\text{em}} = \frac{\bar{\mu}_\nu^2 \omega_p^4}{48\pi^3} \int_0^\infty \frac{k^2 dk}{e^{\frac{1}{T}\sqrt{\omega_p^2 + k^2}} - 1}, \quad (3)$$

where the effective neutrino magnetic moment $\bar{\mu}_\nu = \sqrt{\mu_\nu^2 + d_\nu^2}$.

3. The upper (relative) bound on $\bar{\mu}_\nu$ will be found from the following requirement: the luminosity (3) should be lower than that in a weak channel Q_w . Comparing Eq. (3) with the result for Q_w from [6], we obtain

$$\hat{\mu}_\nu = \bar{\mu}_\nu/\mu_B < 1.58 \times 10^{-12} T_8 F(p) \geq 3.60 \times 10^{-12} T_8. \quad (4)$$

Here, μ_B is the Bohr magneton, the function $F(p) = p \left[\bar{g}_V^2 + \frac{2}{3} \bar{g}_A^2 \frac{B_4(p)}{B_2(p)} \right]^{1/2}$ with

$$B_n(p) = \int_0^\infty \frac{x^n dx}{\exp(p\sqrt{1+x^2}) - 1},$$

the effective weak couplings $\bar{g}_V^2 \simeq 0.929$, $\bar{g}_A^2 = 3/4$,

the argument (see Eq. (2)) $p = \omega_p/T = 1.92(1 + 0.44H_{13}^2\rho_6^{-2})^{-1/4}H_{13}^{1/2}T_8^{-1}$ (under the conditions of the neutron star crust [3, 4], the electron density is expressed through the matter density ρ and the proton mass m_p : $n_e \simeq 0.5\rho/m_p$), and $H_{13} = H/(10^{13}$ G), $T_8 = T/(10^8$ K), $\rho_6 = \rho/(10^6$ g/cm³).

For the case $\omega_p \ll T$ ($p \ll 1$), we obtain from (4) the bound:

$$\hat{\mu}_\nu < 3.6 \times 10^{-12} T_8. \quad (5)$$

In particular, at $T_8 = 1.8$ (as in [7]) we get the bound $\hat{\mu}_\nu < 6.5 \times 10^{-12}$, which is slightly weaker than that found in [7] ($\hat{\mu}_\nu < 1.1 \times 10^{-12}$) from the comparison of the electromagnetic and weak mechanisms of the photoproduction $\gamma e \rightarrow e\nu\bar{\nu}$, which is more effective under the same conditions than the plasmon decay [6].

For the case $\omega_p \gg T$ and a nonrelativistic electron gas ($p_F \ll m$, that is $H_{13}/\rho_6 \gg 1$), from (4) it follows

$$\hat{\mu}_\nu < 3.61 \times 10^{-12} \rho_6^{1/2}. \quad (6)$$

For $\omega_p \gg T$ and $p_F \gg m$ (a relativistic gas), we obtain

$$\hat{\mu}_\nu < 2.94 \times 10^{-12} H_{13}^{1/2}. \quad (7)$$

The analysis shows that the conditions $p_F \gg m$ and (1) can be simultaneously satisfied only at a rather strong field H . For example, at $H_{13} = 300$, Eq. (7) gives $\hat{\mu}_\nu < 5.1 \times 10^{-11}$, which is close to the bounds $\mu_\nu < 5.4 \times 10^{-11} \mu_B$ and $\mu_{\bar{\nu}_e} < 2.9 \times 10^{-11} \mu_B$ that were obtained from the analysis of solar neutrinos [10] and in the GEMMA laboratory experiment on antineutrino scattering off electrons [11], respectively.

4. Relative upper bounds on the effective neutrino magnetic moment (see Eqs. (4)–(7)) determine the range of its values where the weak channel of the plasmon decay is more effective than the electromagnetic one. In conclusion, we note that production of a neutrino pair by a high-energy photon was considered in [12]. As opposed to the plasmon decay discussed above, this process is caused by coherent interaction of a neutrino possessing a magnetic moment with a dense medium.

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